LS-116
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# Recalculation of Shielding for the Addition of a PAR

## 1.0 Introduction

The shielding estimates for the Electron and Positron Linacs and the Booster Synchrotron, contained in the 1987 Conceptual Design Report (CDR) of the APS (ANL-87-15), have been reviewed and recalculated, along with newly initiated calculations of the required shielding for the addition of a Positron Accumulator Ring (PAR). Several new assumptions with respect to beam intensity, projected losses in the system, and assumed operational time have been incorporated into the calculations. Details of the previous calculations, which describe the methodology used, may be found in APS Light Source Note LS-90.

## 2.0 Shielding Design Objective

The Department of Energy's (DOE) guidance (DOE 81), concerning the ALARA design goal for new facilities, states that the design objective is to limit exposures to one-fifth of the 5-rem-per-year limit given in the same document. This implies an average dose rate limit of 0.5 mrem/h, based on a 40-h work week. Sufficient concrete as a bulk shield is used to achieve reasonable global shielding of accelerator components for distributed losses in the system. Localized shielding, which may consist of iron, lead and/or dense polyethylene, is used at high loss points to supplement the global shield. In some cases, exclusion zones may be required during the operational time of the particular component in order to meet the guideline.

An additional consideration used in the shielding estimates was to limit the dose received by any individual, due to any single beam dump loss, to less than 100 mrem.

## 3.0 Types of Radiation Considered

Depending upon the energy of the accelerated particles, one or more of three radiation components, each with differing attenuation lengths in a given medium, must be dealt with. These are bremsstrahlung (BREM), giant resonance neutrons (GRN), and high energy neutrons (HEN). High energy electrons and positrons produce photons which in turn produce more electrons and positrons which produce more photons. The electromagnetic shower which develops contains a spectrum of bremsstrahlung photons with energies up to the incident particle energy. This bremsstrahlung is highly peaked in the forward direction of the particle beam, but the transverse component cannot be neglected. Giant resonance neutrons are produced by photonuclear interactions (threshold energy in most materials in the range 7-20 MeV). They are emitted almost isotropically and have an average energy of about 2 MeV. For electrons or positrons above several hundred MeV, high energy neutrons ($E > 100$ MeV) are produced. The high energy component is not isotropic, but in many shielding situations, only the transverse component is important. For shielding estimates in this review, both the GRN and HEN components are generally taken to be isotropic. The bulk shielding provided for the above mentioned components will also adequately attenuate any synchrotron radiation which escapes from the vacuum chamber in which the particles are accelerated.

## 4.0 Radiation Dose Equivalent Factors

The unshielded radiation dose equivalent factors for the above components have been adapted from Fasso, et al. (FAS 84), with their suggested modifications. These are:

| Radiation Component | Dose Equivalent Conversion Factor, $F_H$ $\frac{(\text{mrem m}^2)}{\text{J}}$ |
|---|---|
| Bremsstrahlung | 2.8 |
| Giant Resonance Neutrons | 0.63 |
| High Energy Neutrons | 0.075 |

These factors express the unshielded dose rates at 1 m in the transverse direction (90°) to the electron or positron beam. In the forward direction

(0°) with respect to the particle beam, the bremsstrahlung radiation is quite intense and

$$F_{BREM} = 8.3\ E_0 \left(\frac{\text{mrem m}^2}{\text{J}}\right),$$

in which $E_0$ is the initial energy of the particle in MeV. For the GRN and HEN components in the forward direction, the dose factors in the table above are used.

## 5.0 Radiation Attenuation Parameters

Information on the attenuation of bremsstrahlung, giant resonance neutrons, and the high energy neutrons by different shielding was taken from the literature, when available. The literature sources consulted for the attenuation lengths include ALS 73, BAT 67, BAT 70, DIN 77, FAS 84, Nel 68, SWA 79, SWA 85, TES 79 and others.

With respect to attenuation of the high energy neutrons, attenuation lengths were not available in the literature for every material of interest. In the absence of quoted values, the attenuation lengths for the high-energy-neutron radiation component (E > 150 MeV) were estimated from the expression: $\lambda = 38.5\ A^{0.3}\ \text{g/cm}^2$, adapted from ICRU Report 28 (ICR 78), in which A is the mass number of the attenuating material.

In all cases, an attempt was made to use conservative values for the attenuation lengths quoted in the literature. The following attenuation lengths were used:

Attenuation Lengths

| Radiation Component | Shielding Material | Attenuation Length $\lambda(g/cm^2)$ |
| --- | --- | --- |
| Bremsstrahlung | Lead | 25 |
| | Concrete | 49 |
| | Iron | 37 |
| | Sand (Earth) | 70 |
| Giant Resonance Neutrons | Concrete | 40 |
| | Dense Polyethylene | 6.3 |
| | Sand (Earth) | 33 |
| | Iron (backed by H) | 100 |
| | Lead (backed by H) | 161 |
| High Energy Neutrons | Concrete | 65 (E < 100 MeV) |
| | | 115 (E > 100 MeV) |
| | Iron | 138 |
| | Lead | 191 (E > 150 MeV) |
| | Dense Polyethylene | 62 (E > 150 MeV) |

## 5.1 Shielding Computations

Bulk shielding computations were based on the following expression for point losses in the various components of the APS system:

$$\dot{H} = \sum_i \frac{F_{H_i} W e^{-d/\lambda_i}}{r^2},$$

in which $\dot{H}$ has units of mrem/h, if W, the energy loss rate, is expressed in J/h, $F_{H_i}$ is the appropriate dose conversion factor from the table, for the $i^{th}$ radiation component, r is the source to dose point distance in m, d is the shield thickness in $g/cm^2$, and $\lambda_i$ is the attenuation length for the $i^{th}$ radiation component, in $g/cm^2$.

## 6.0 Shielding of Linacs and Positron Converter

### 6.1 Assumptions and Parameters

The revised physical parameters used to recalculate the shielding for the electron linac, the positron converter and the positron linac are:

Electron Linac:

Pulse Amplitude: 1.2 A

Pulse Width: 40 ns

Pulse Repetition Rate: 24 per 1/2 s = 48 pps

Charge per Pulse: $3 \times 10^{11}$ e-/ pulse

Average Current: $I = 1.2(40 \times 10^{-9})48 = 2.3\ \mu A$ e-

Maximum Energy: 200 MeV

Electron Beam Power at Target: 2.3 μA (200 MeV) = 460 W

Positron Converter:

Conversion Ratio: 0.0083 e +/e -

Transmission to Positron Linac: 60%, which gives a net conversion of 0.005 e+/e-

Positron Linac:

Positron Charge per Output Pulse: $1.5 \times 10^{9}$ e+/pulse

Positron Average Current: I = 11.5 nA e+

Maximum Energy: 450 MeV

Tunnel Parameters:

Dimensions: 9' by 9'

Beam Height: 5' above floor level

Distance from Beam Line to Inner Shield Wall: 1.7 m

### 6.2. Estimated Beam Losses in Linac System

For the various components in the Linac system, shielding computations were based upon point losses of a certain fraction of the beam power. These are indicated in the table below:

Estimated Losses in the Linac System Components

| Component | $\bar{I}$ (μA) | Loss (%) | $\bar{E}$ (MeV) | Average Power Loss (W) | |
|---|---|---|---|---|---|
| | | | | e+ | e- |
| Gun Output | 5.69 | | | | |
| | | 55 | 0.15 | | 0.47 |
| Buncher | 2.56 | | | | |
| | | 10 | 100 | | 25.6 |
| First Linac Output | 2.3 | | | | |
| | | 100 | 200 | | 460 |
| Second Linac | $1.91 \times 10^{-2}$ | | | | |
| Input | | 40 | 60 | 0.46 | |
| Transmitted | $1.15 \times 10^{-2}$ | | | | |

## 6.3 Shielding Recalculations

### 6.3.1 Electron Linac

In LS-90, the Electron Linac shielding was determined to be 2 m of concrete, and the distance to the nearest dose point was taken as 4 m. For the Klystron Gallery side, the shielding is 2 m of concrete. On the opposite side of the linac, the shielding is part concrete, part earth berm which increases the total distance to the dose point. For the revised value of power lost, 25.6 W, the computed dose rates are

$$\dot{H}_{BREM} = \frac{2.8\ (25.6)\ (3.6 \times 10^3)\ e^{-\frac{2.35\ (200)}{49}}}{(4)^2} = 1.101 \text{ mrem/h}$$

$$\dot{H}_{GRN} = \frac{0.63\ (25.6)\ (3.6 \times 10^3)\ e^{-\frac{2.35\ (200)}{40}}}{(4)^2} = 0.029 \text{ mrem/h}$$

$$\dot{H}_{HEN} = \frac{0.075\ (25.6)\ (3.6 \times 10^3)\ e^{-\frac{2.35\ (200)}{65}}}{(4)^2} = 0.313 \text{ mrem/h,}$$

for a total of 1.44 mrem/h, on the Klystron Gallery side. Assuming an operational time of 10 %, the average dose rate would be 0.14 mrem/h, within the guideline. With the addition of localized lead shielding, the dose rate can be reduced to within the guideline even for continuous operation of the linac. With respect to the earth berm side of the shielding, the dose rate will be within the guideline without any local shielding.

### 6.3.2 Positron Converter

At the positron converter, we assume a loss of 460 W. If an additional 30 cm thickness of concrete is added to the shield on the Klystron Gallery side, the total shielding in the converter area will then be 30 cm of iron backed up by 200 cm of concrete. This added shielding will be 10 m in length, starting at the beginning of the converter area. No added shielding will be needed on the earth berm shield side. For the increased shielding, the dose rates become

$$\dot{H}_{BREM} = \frac{2.8\ (460)\ (3.6 \times 10^3)\ e^{-\frac{7.8\ (30)}{37}}\ e^{-\frac{2.35\ (200)}{49}}}{(4)^2} = 0.035 \text{ mrem/h}$$

$$\dot{H}_{GRN} = \frac{0.63\ (460)\ (3.6 \times 10^3)\ e^{-\frac{7.8\ (30)}{100}}\ e^{-\frac{2.35\ (200)}{40}}}{(4)^2} = 0.050 \text{ mrem/h}$$

$$\dot{H}_{HEN} = \frac{0.075\ (460)\ (3.6 \times 10^3)\ e^{-\frac{2.35\ (230)}{65}}}{(4)^2} = 1.900 \text{ mrem/h,}$$

giving a total of 1.985 mrem/h. For an assumed operational time of 10%, the average dose rate would be 0.199 mrem/h which is within the guideline. The dose rate can also be reduced to within the guideline by using localized lead shielding around the converter target.

### 6.3.3 Positron Linac

For the Positron Linac, the previous amount of shielding was more than adequate for the positron beam but was kept at 2 m to provide shielding for the expected losses in the accompanying electron component. For the increased intensity in the new design, the 2 m is still adequate for shielding.

### 6.3.4 Positron Beam Compression System

At the beam compression system, the loss is assumed to be 10% of the positron beam, which amounts to 0.518 W(11.5 nA x 450 MeV x 0.1). In addition, the accompanying electron beam, assumed to be equal in magnitude to the positron beam, is entirely lost at a dump in this same region. This gives an additional loss of 5.18 W, for a total of 5.7 W. The resulting dose rates are:

$$\dot{H}_{BREM} = \frac{2.8\ (5.7)\ (3.6 \times 10^3)\ e^{-\frac{2.35\ (200)}{49}}}{(4)^2} = 0.245 \text{ mrem/h}$$

$$\dot{H}_{GRN} = \frac{0.63\ (5.7)\ (3.6 \times 10^3)\ e^{-\frac{2.35\ (200)}{40}}}{(4)^2} = 0.006 \text{ mrem/h}$$

$$\dot{H}_{HEN} = \frac{0.075\ (5.7)\ (3.6 \times 10^3)\ e^{-\frac{2.35\ (200)}{65}}}{(4)^2} = 0.070 \text{ mrem/h},$$

for a total of 0.321 mrem/h, which meets the guideline.

## 6.4 PAR Shielding Considerations

The shielding estimates for the PAR are based upon a total of $7.2 \times 10^{10}$ e+/s of energy 450 MeV being delivered to the PAR. These parameters give a beam power of 5.184 W, of which 50% is assumed to be lost at point P in Fig. 1 below.

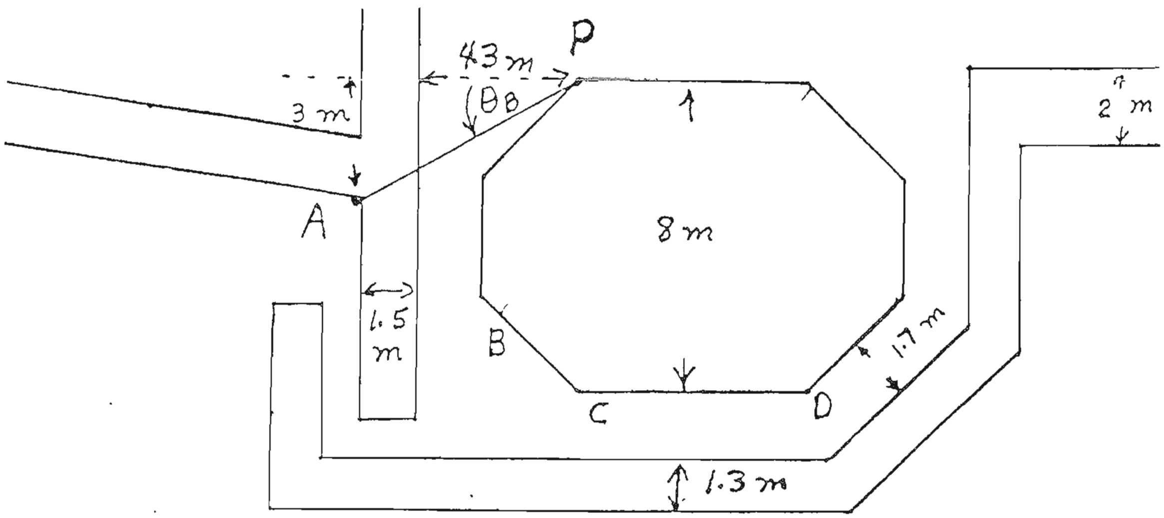


Figure 1. Shielding layout for the addition of a PAR.

This assumption is based on experience at DESY which would indicate that most of the loss takes place in this region and that following this, about 99% of the remainder is delivered to the synchrotron. For the geometry shown in the figure, the forward directed bremsstrahlung will be intercepted by sufficient concrete to nullify any significant contribution to the dose rate in that direction. The nearest dose point of concern is A in the figure. To estimate the bremsstrahlung contribution at point A, the following empirical expression, adapted from Swanson, et al. (SWA 85), which expresses the angular dependence of the bremsstrahlung dose equivalent factor, was used:

$$F_{H_i} = 16.7E_0 \; (2^{-\theta_B/\theta_{1/2}}) + 833 \; (10^{-\theta_B/21}) + 25 \; (10^{-\theta_B/110})$$

in which $F_{H_i}$ is in (mrem $m^2/J$) at 1 m, $E_0$ is the positron energy in MeV, $\theta_B$, is the bremsstrahlung emission angle with respect to the original positron beam direction, in degrees and $\theta_{1/2}\,E_0$ = 100 MeV deg. The first term of the expression accounts for the intense, highly peaked forward component of the bremsstrahlung, the remaining terms express the contribution as a function of $\theta_B$. For point A in Fig. 1, the distance from the loss point is 6.53 m and $\theta_B$ is taken as 27.35 degrees. The bremsstrahlung dose factor at this angle is then:

$$F_{H_{BREM}} = 16.7(450)(2^{-\frac{27.35(450)}{100}}) + 833(10^{-\frac{27.35}{21}}) + 25(10^{-\frac{27.35}{110}})$$

$$= 55.6\ \frac{\text{mrem}\cdot\text{m}^2}{\text{J}}.$$

The dose rates for an assumed side wall shielding of 1.5 m of concrete and a 50% loss at a point are:

$$\dot{H}_{BREM} = \frac{55.6(0.5)(5.184)(3.6\text{x}10^3)\ e^{-\frac{2.35(150)\sec 27.35^0}{49}}}{(6.53)^2} = 3.696\ \text{mrem/h}$$

$$\dot{H}_{GRN} = \frac{0.63(0.5)(5.184)(3.6\text{x}10^3)\ e^{-\frac{2.35(150)\sec 27.35^0}{40}}}{(6.53)^2} = 0.007\ \text{mrem/h}$$

$$\dot{H}_{HEN} = \frac{0.075(0.5)(5.184)(3.6\text{x}10^3)\ e^{-\frac{2.35(150)\sec 27.35^0}{65}}}{(6.53)^2} = 0.037\ \text{mrem/h}.$$

The total dose rate is 3.74 mrem/h, but for an operational time of 10%, the average dose rate is reduced to 0.374 mrem/h, which is within the guidelines. Because of the increased distance from point P in Fig. 1 to other dose points outside of the PAR, only 1.3 m of shielding is needed for the remaining shielding walls of the PAR.

With respect to the roof shielding of the PAR, the shielding is designed so that the area may be occupied while the accelerator is in operation. Assuming a roof shielding of 1.5 m of concrete and a total distance of 2.72 m to the dose point, the computed total dose rate is 3.188 mrem/h on the roof directly above the point P in Fig. 1. Assuming an operational time of 10% of continuous, the average dose rate turns out to be 0.32 mrem/h, within the guideline.

Although no beam loss in the PAR is expected to result in a forward directed beam other than at point P in Fig. 1, lead beam stops (10-15 cm thick) which will greatly attenuate the bremsstrahlung component can be provided for the three positions (B, C and D) where a problem might develop.

### 6.5 Booster Injection

The assumed loss rate at the Injector was taken as 50% in LS-90. Using this same assumption with the increased intensity, the power loss now becomes:

$$W = 7.2\text{x}10^{10}(0.5)(450)(1.6\text{x}10^{-13})(3.6\text{x}10^{3}) = 9.33\text{x}10^{3}\ \text{J/h}.$$

For a shield of 1.5 m of concrete and a minimum distance of 3.2 m to the dose point, the dose rates are:

$$\dot{H}_{BREM} = \frac{2.8\ (9.33 \text{ x } 10^{3})\ e^{-\frac{2.35\ (150)}{49}}}{(3.2)^{2}} = 1.916 \text{ mrem/h}$$

$$\dot{H}_{GRN} = \frac{0.63\ (9.33 \text{ x } 10^{3})\ e^{-\frac{2.35\ (150)}{40}}}{(3.2)^{2}} = 0.085 \text{ mrem/h}$$

$$\dot{H}_{HEN} = \frac{0.075\ (9.33 \text{ x } 10^{3})\ e^{-\frac{2.35\ (150)}{65}}}{(3.2)^{2}} = 0.302 \text{ mrem/h},$$

which gives a total dose rate of 2.303 mrem/h. For an operational time of 10% of continuous, the average dose rate would be 0.23 mrem/h, which is within the guideline. If 10 cm of lead were used as local shielding, the photon dose rate could be reduced to about 0.02 mrem/h, and the total dose rate would then meet the guideline without averaging.

## 6.6 Booster Extraction

The Booster Extraction region presents the most formidable problem of shielding because of the high energy of the positrons. Any losses in the transfer of positrons to the storage ring result in the formation of a relatively large HEN component (because of the high energy of the positrons). This component is very difficult to shield, since for any material the attenuation lengths are relatively large, thereby requiring large thicknesses to realize significant attenuation. Moreover, the losses occurring in this region generally transpire within a short time period which can lead to the production of significant dose rates, which tend to be dominated by the neutron component. The attenuation length of the high energy component in concrete is 115 g/cm$^2$, in iron it is 138 g/cm$^2$, and, in lead, 191 g/cm $^2$. The table which follows indicates the dose rates produced assuming certain fractional losses at a point. The relevant assumptions for the significant parameters are that the shield consists of 1.5 m of concrete and the minimum distance to the dose point is 3.2 m. Total beam power is obtained from:
$W = 7.2 \times 10^{10}$ (7000) $(1.6 \times 10^{-13})$ $(3.6 \times 10^3) = 2.9 \times 10^5$ J/h.

Dose Rate in mrem/h

| Beam Loss Fraction | BREM | GRN | HEN | TOTAL |
|---|---|---|---|---|
| 0.5 | 40.9 | 1.3 | 49.5 | 91.7 |
| 0.4 | 32.7 | 1.1 | 39.6 | 73.4 |
| 0.3 | 24.5 | 0.8 | 29.7 | 55.0 |
| 0.2 | 16.4 | 0.5 | 19.8 | 36.7 |
| 0.1 | 8.2 | 0.3 | 9.9 | 18.4 |
| 0.05 | 4.1 | 0.1 | 5.0 | 9.2 |

By using local shielding, an assuming that the operational time is 10%, the average dose rates can be reduced to those shown in the following table:

Dose Rate in mrem/h

| Beam Loss Fraction | BREM | GRN | HEN | Total | $\bar{\dot{H}}$ (10% OPER) |
|---|---|---|---|---|---|
| 0.5 | - | 0.078 | 4.604 | 4.682 | 0.47 |
| 0.4 | - | 0.063 | 3.683 | 3.746 | 0.37 |
| 0.3 | - | 0.048 | 2.762 | 2.810 | 0.28 |
| 0.2 | - | 0.032 | 1.841 | 1.873 | 0.19 |
| 0.1 | - | 0.016 | 0.921 | 0.937 | 0.09 |

From the table, it is evident that the HEN component contributes the majority of the radiation dose rate and the bremsstrahlung component contribution can be made negligible if sufficient lead is supplied as local shielding (in this example, 40 cm of lead was used). Even with the pessimistic assumption of 50% loss at a single point, the average dose rate will still be within the guidelines for a sufficient amount of local shielding at the assumed loss point. Since it is not known what the fractional beam loss at extraction will be, the amount of local shielding, if any, that will be required cannot be exactly estimated. However, experience at DESY indicates that the losses may even be smaller than those considered in the table above. If this proves to be the case for the APS, only a small amount of local shielding, if any, may be required. The recommended concrete shielding is 1.5 m in the extraction region, supplemented by local shielding of "hot" spots as needed.

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